Gradient-Based Propeller Optimization with Acoustic Constraints

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Daniel Ingraham[1] Justin Gray[1] Leonard V. Lopes[2]

[1]NASA Glenn Research Center [2]NASA Langley Research Center

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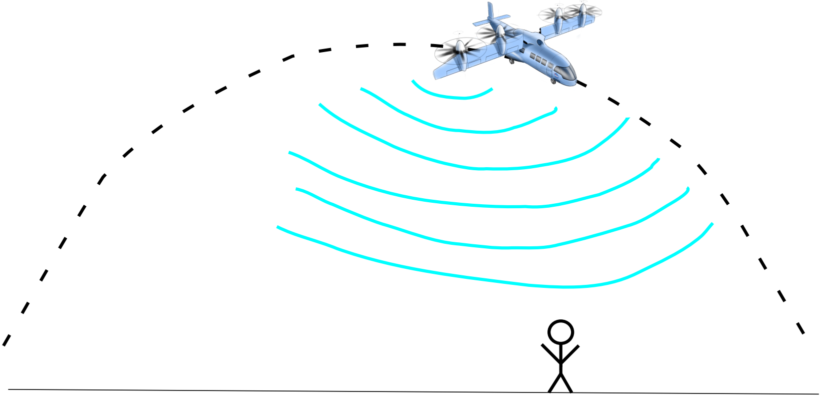
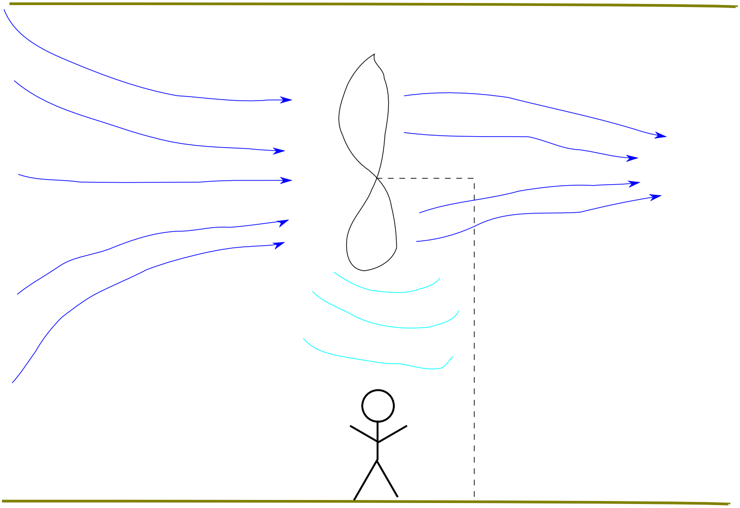
Urban Air Mobility Represents a New Challenge for Aircraft Acoustics

What We'd Like To Do

Develop toolchain for large-scale **optimization** of a tilt wing turboelectric UAM concept from Johnson et al.[1], with coupled structural, aerodynamics, acoustics, propulsion, thermal, and trajectory disciplines.



What We've Done Here: Propeller Optimization With Fixed Relative Observer (Essentially Wind Tunnel Configuration)



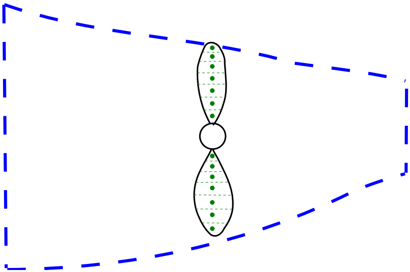
Mid-Fidelity Models, Gradient-Based Optimization Enable Large-Scale Analysis

- Mid-fidelity aerodynamic models:
  - Blade element momentum theory (BEMT): Gur and Rosen[2, 3], Wisniewski et al.[4].
  - Vortex lattice: Miller and Sullivan[5].
- High-fidelity aerodynamic models:
  - Computational Fluid Dynamics: Pagano et al.[6, 7].
- Most examples use some form of the Ffowcs-Williams Hawking (FWH) approach[8] for the acoustic model.

Methods for this work

BEMT and FWH, all with analytic derivatives. Focusing on developing tool chain.

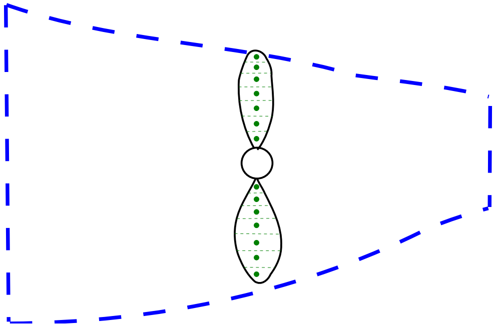
Propeller Aerodynamics: Blade Element Momentum Theory



BEMT Limitations

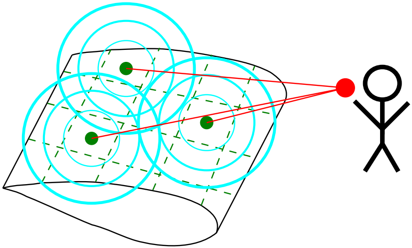
- No interaction between blade elements, so spanwise flow not captured (so no blade sweep).
- Here, used steady, level flight, so predicted loads will be steady (not changing with propeller rotation).
- OK for steady, forward flight. Probably not adequate for VTOL.

BEMT Implementation: OpenBEMT



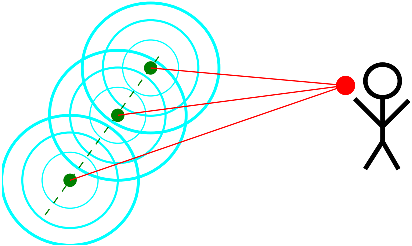
- Initially developed by Hwang and Ning[9] to study the X-57 Maxwell concept.
- Uses OpenMDAO framework[10] to propagate outputs and their derivatives through each stage of the calculation for gradient-based optimization.

Propeller Acoustics: Ffowcs-Williams Hawking Approach



- Uses distributed flow properties on surface (e.g., propeller blade surface) to calculate source term strengths, and then the acoustic pressure time history at a specified location ("acoustic observer").

Compact F1A

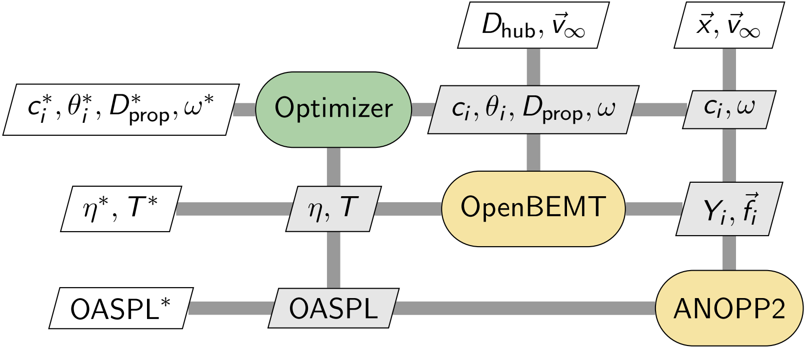


- Acoustic prediction method used here: compact version[11] of Farassat's 1A formulation[12, 13] of the FWH approach.
- Needed inputs directly correspond to BEMT outputs, and about the same computational expense as BEMT.
- Limitations & Assumptions
  - Steady loading configuration captures only steady acoustic sources.
  - Elongated surface in lifting line direction.
  - Assumes acoustic observer distance much larger than blade thickness.

FWH Implementation: ANOPP2

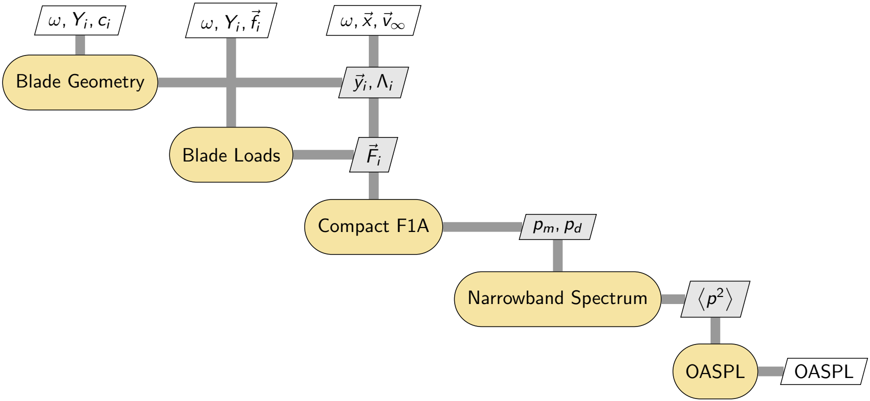
- Compact F1A calculation is implemented in NASA Langley's second generation Aircraft Noise Prediction Program[14] (ANOPP2).
- ANOPP2 is a comprehensive noise prediction framework, much more than just F1A.
- The Compact F1A implementation has been differentiated for use with gradient-based optimization, and is used in this work.

XDSM Diagram: Optimization Overview



- D_{hub}: hub diameter
- $\vec{v}_\infty$: free-stream velocity
- c_i: chord
- Y_i: blade element location
- T: thrust
- D_{prop}: propeller diameter
- $\vec{x}$: observer location
- θ_i: twist
- $\vec{f}_i$: blade element loading
- η: efficiency

XDSM Diagram: ANOPP2 Detail



Test Case: X-57 Cruise Propeller Properties

Test case parameters were taken from the NASA's X-57 Maxwell[15] cruise propellers:

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Test case parameters were taken from the NASA's X-57 Maxwell[15] cruise propellers:

Property	Value
Altitude	10 m
Cruise speed	77.2 m/s
Diameter	1.5 m
Hub diameter	0.3 m
Airfoil	MH117
Blade count	3

Two Optimization Cases

Multi-objective optimization: **maximize propeller efficiency** for **constant thrust**, with **OASPL constraint** systematically reduced to form a Pareto frontier.

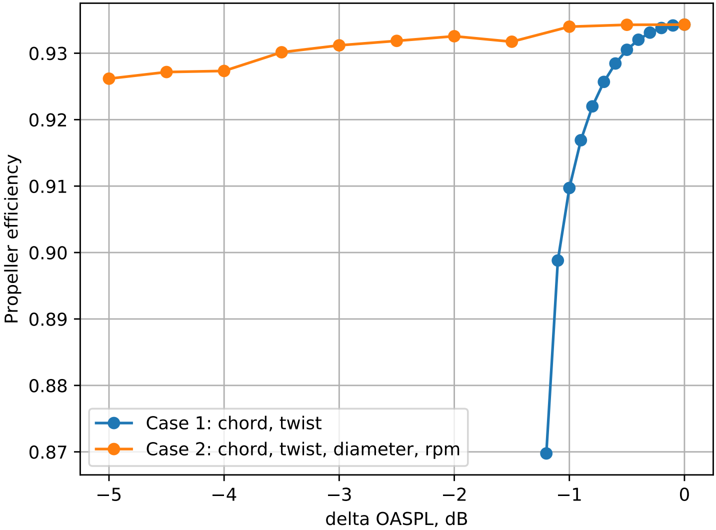
	Variable	Lower Bound	Upper Bound
maximize	efficiency		
with respect to	chord	1 cm	20 cm
	twist	20 deg	90 deg
	Case 2 only: diameter[1]	75 cm	150 cm
	Case 2 only: RPM	None	None
subject to	total thrust = 700. N		
	sideline OASPL	$x\ \Delta$dB	$x\ \Delta$dB

[1] Optimizer chose upper bound for each run.

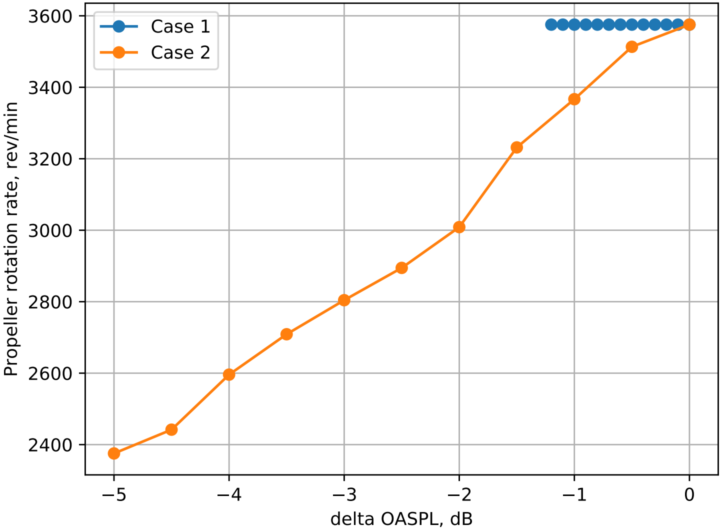
Optimizations are Pretty Quick

```
   Itns Major Minors     Step   nCon Feasible  Optimal  MeritFunction     L+U BSwap     nS condZHZ Penalty
     10     0     10               1  3.3E-02  5.5E-03 -9.3427573E-01       4            9 1.9E+00         _  r
     11     1      1 1.7E-01       3  2.8E-02  4.8E-03 -9.3413416E-01       4            9 1.8E+00 1.2E-01 _  r
     12     2      1 1.7E-01       5  2.4E-02  1.8E-01 -9.3408573E-01       4            9 1.7E+00 1.8E-01 _s
     13     3      1 4.3E-02       7  2.4E-02  4.4E-02 -9.3401303E-01       4     1      9 2.6E+00 2.9E-01 _
     14     4      1 2.5E-01       9  2.0E-02  5.1E-02 -9.3403539E-01       4            9 3.6E+00 2.9E-01 _
     16     5      2 7.3E-02      11  1.9E-02  1.1E-01 -9.3403816E-01       4           10 4.5E+00 2.9E-01 _
     18     6      2 1.0E+00      12  2.0E-03  4.6E-02 -9.3394566E-01       4            9 4.8E+00 5.9E-01 _
     20     7      2 1.0E+00      13  1.1E-03  3.9E-03 -9.3397863E-01       4     1     10 7.4E+00 5.9E-01 _
     21     8      1 1.0E+00      14  6.6E-05  1.4E-02 -9.3397529E-01       4           10 7.6E+00 8.4E+00 _
     22     9      1 1.0E+00      15  7.0E-05  3.7E-02 -9.3398045E-01       4           10 8.7E+00 2.9E+00 _
     23    10      1 1.0E+00      16  2.6E-05  2.8E-02 -9.3398412E-01       4           10 6.2E+00 2.9E+00 _
     24    11      1 1.0E+00      17  1.5E-04  2.0E-02 -9.3398490E-01       4           10 7.6E+00 2.9E+00 _
     25    12      1 1.0E+00      18  1.0E-05  2.7E-02 -9.3398664E-01       4           10 1.0E+01 2.9E+00 _
     26    13      1 2.3E-01      20  1.2E-05  1.8E-02 -9.3398804E-01       4           10 8.3E+00 2.9E+00 _
     27    14      1 1.0E+00      21  3.5E-06  1.9E-03 -9.3398892E-01       4           10 1.2E+01 2.9E+00 _
     28    15      1 1.0E+00      22  1.8E-05  5.8E-03 -9.3398934E-01       4           10 1.3E+01 2.9E+00 _
     29    16      1 1.0E+00      23  1.5E-05  3.0E-04 -9.3398972E-01       4           10 1.5E+01 2.9E+00 _
     30    17      1 1.0E+00      24 (3.3E-07) 1.4E-04 -9.3398994E-01       4           10 1.7E+01 2.9E+00 _
     31    18      1 1.0E+00      25 (1.0E-07) 3.3E-03 -9.3399005E-01       4           10 2.2E+01 2.9E+00 _
     32    19      1 1.0E+00      26  1.0E-06  4.2E-04 -9.3399037E-01       4           10 3.8E+01 2.9E+00 _

   Itns Major Minors     Step   nCon Feasible  Optimal  MeritFunction     L+U BSwap     nS condZHZ Penalty
     34    20      2 1.0E+00      27  1.1E-06  4.4E-03 -9.3399069E-01       4            9 2.1E+01 2.9E+00 _
     35    21      1 1.0E+00      28 (8.3E-07) 4.8E-03 -9.3399109E-01       4            9 2.0E+01 2.9E+00 _
     36    22      1 1.0E+00      29 (7.2E-07) 1.6E-04 -9.3399126E-01       4            9 1.9E+01 2.9E+00 _
     37    23      1 1.0E+00      30 (3.1E-08) 4.5E-04 -9.3399127E-01       4            9 1.8E+01 2.9E+00 _
     38    24      1 1.0E+00      31 (1.6E-09) 4.0E-05 -9.3399127E-01       4            9 4.1E+01 2.9E+00 _
     39    25      1 1.0E+00      32 (9.1E-09) 2.1E-04 -9.3399127E-01       4            9 5.5E+01 2.9E+00 _
     40    26      1 1.0E+00      33 (1.3E-09) 2.2E-04 -9.3399127E-01       4     1      9 6.0E+01 2.9E+00 _
     41    27      1 1.0E+00      34 (1.6E-09) 1.2E-04 -9.3399127E-01       4            9 5.7E+01 2.9E+00 _
     42    28      1 1.0E+00      35 (6.0E-10) 2.1E-05 -9.3399127E-01       4            9 4.9E+01 2.9E+00 _
     43    29      1 1.0E+00      36 (2.9E-10) 3.7E-05 -9.3399127E-01       4            9 5.3E+01 2.9E+00 _
     44    30      1 1.0E+00      37 (1.7E-10) 5.9E-05 -9.3399127E-01       4            9 6.1E+01 2.9E+00 _
     45    31      1 1.0E+00      38 (4.2E-10) 5.3E-05 -9.3399127E-01       4            9 5.8E+01 2.9E+00 _
     46    32      1 1.0E+00      39 (3.6E-10) 2.4E-05 -9.3399127E-01       4            9 4.8E+01 2.9E+00 _
     47    33      1 1.0E+00      40 (7.2E-11) 2.8E-06 -9.3399127E-01       4            9 4.7E+01 2.9E+00 _
     48    34      1 1.0E+00      41 (2.8E-12)(6.7E-07)-9.3399127E-01       4            9 4.8E+01 2.9E+00 _
1

 SNOPTC EXIT   0 -- finished successfully
 SNOPTC INFO   1 -- optimality conditions satisfied

 Time for MPS input                             0.00 seconds
 Time for solving problem                       9.54 seconds
 Time for solution output                       0.00 seconds
 Time for constraint functions                  9.54 seconds
 Time for objective function                    0.00 seconds
```

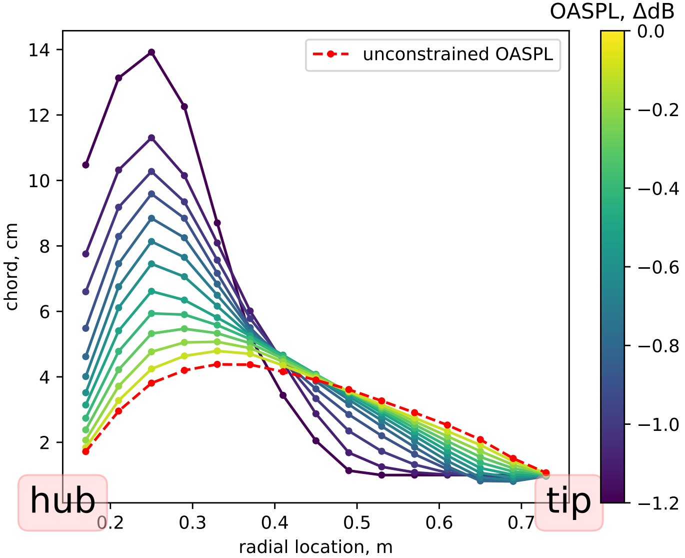
Significant Difference Between the Two Pareto Frontiers



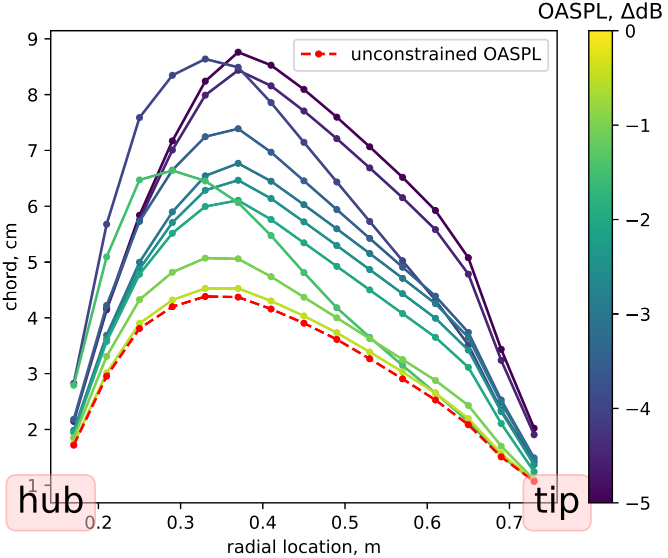
Slower Propellers Are Quiet Propellers



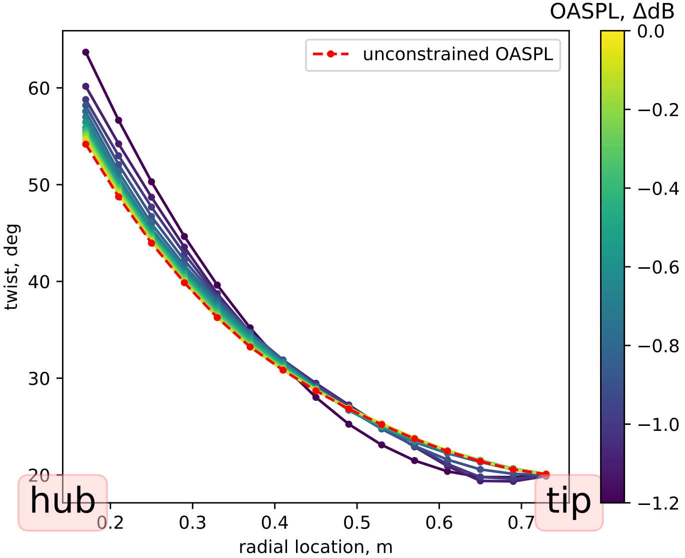
Case 1 Strategy: Shift Chord Inboard to Quiet Propeller



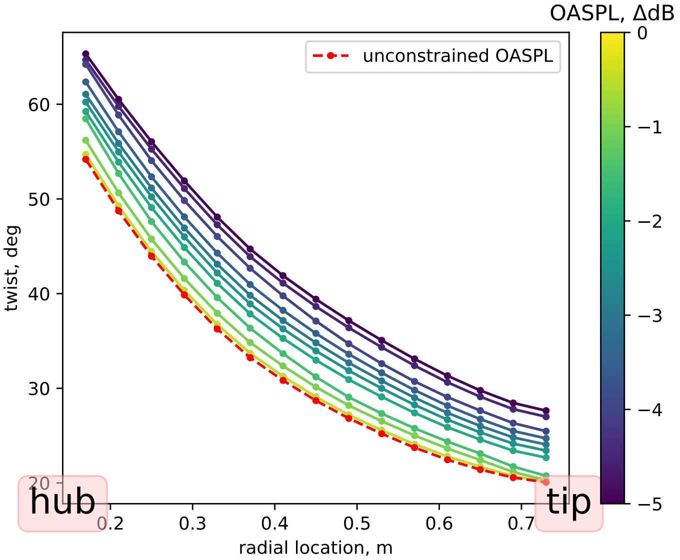
Case 2 Strategy: Increase Chord to Maintain Thrust



Case 1 Strategy: Shift Twist Inboard to Quiet Propeller

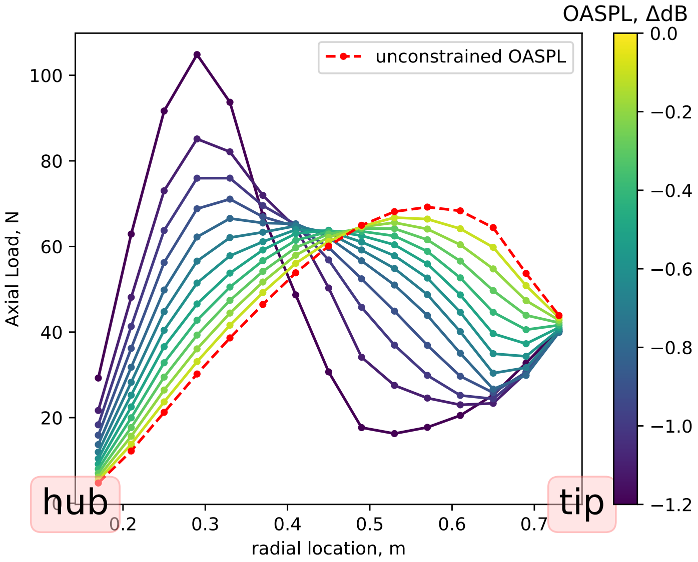


Case 2 Strategy: Increase Twist to Maintain Thrust[2]

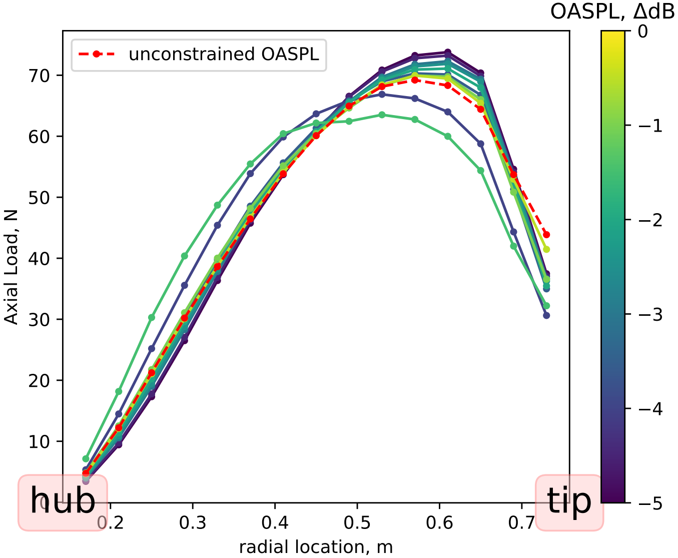


[2]Decreased RPM+increased pitch reminiscent of Berton & Nark[16]

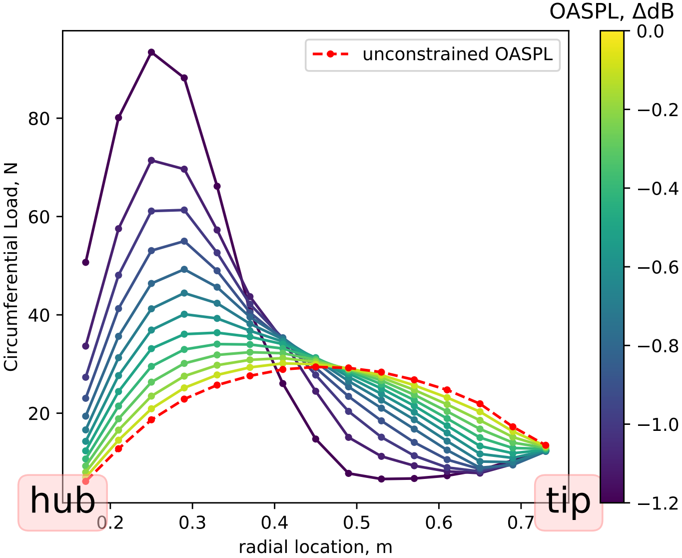
Case 1: Move Axial Loading Inboard



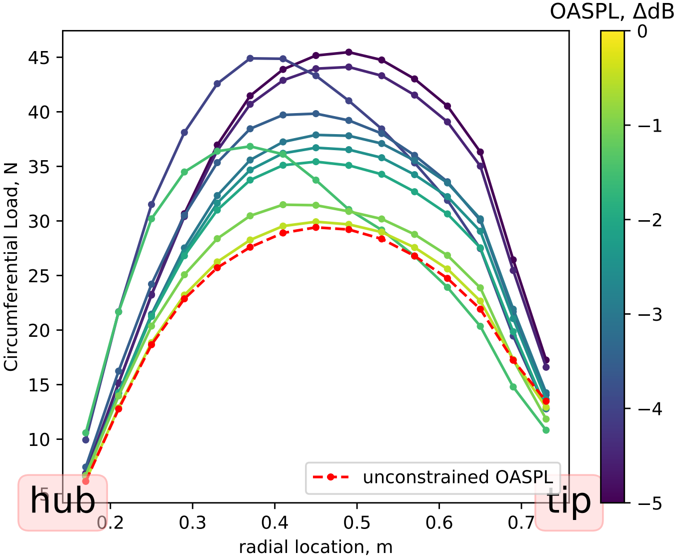
Case 2: Maintain Axial Loading



Case 1: Chord and Twist Impact Circumferential Loading



Case 2: More Chord and Twist Increase Circum. Loading



Conclusions & Future Work

- Propeller aerodynamics and acoustics codes were combined within an MDAO framework and exercised on two test cases.
- Near-term next steps:
  - fixed-observer case with trajectory optimization
    - Goal is to extend Berton & Nark's[16] recent idea of reducing the noise of a hypothetical propeller-driven electrified GA aircraft through pitch control.
  - Replace BEMT with higher-fidelity approach
- Ultimate goal: include this tool chain in a larger UAM optimization (trajectory, power generation, vehicle weight).

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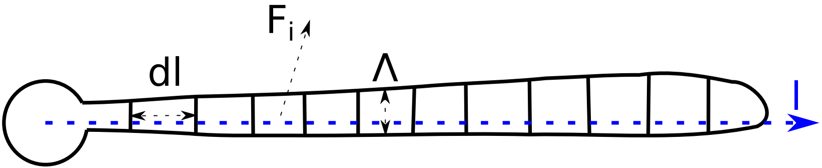
Compact F1A

- Acoustic prediction method used here: compact version[11] of Farassat's 1A formulation[12, 13] of the FWH approach.
- **Compact** F1A: integration surface is replaced with spanwise lifting line.

$$p(t) = \frac{1}{4\pi} \int \left[\rho_\infty \Lambda C_{1A} + \frac{1}{c_\infty} \left(\dot{F}_i D_{1A,\mathrm{i}} + F_i E_{1A,i} \right) \right]_{\mathrm{ret}} \mathrm{d}l$$



C_{1A}, D_{1A}, E_{1A} are function of blade motion only, **large in regions where blade motion is high**.